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An experimental investigation of friction at very slow sliding velocities.

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Massachusetts Institute of Technology

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AN EXPERIMENTAL INVESTIGATION OF FRICTION AT VERY LOW SLIDING VELOCITIES

Gerald R. Jones

AN EXPERIMENTAL INVESTIGATION OF FRICTION AT

VERY LOW SLIDING VELOCITIES

by

Gerald H. Jones

B.S., U.S. Naval Academy, Annapolis, Maryland, 1949

Submitted in partial fulfillment of the requirements for the degree of Naval Engineer

at the

Massachusetts Institute of Technology

1955

ABSTRACT

The object of this thesis is to contribute to the data of friction at very low sliding velocities prior to forming some general conclusions about very slow speed frictional phenomena. To accomplish this, data has been gathered on five different plastics and three metals. The data gathered is presented in the form of $\mu - V$ curves over the velocity range of from 10^{-7} cms. per sec. to 10 cms. per sec. The work was carried out using a very low velocity friction apparatus developed by F. Heymann under the supervision of Professor Rightmire, Professor Rabinowicz, and with the help of the Friction and Lubrication Laboratory. All of this work was started and is being carried on under an Office of Naval Research contract.

The materials tested were found to exhibit widely differing $\mu - V$ curve characteristics as well as widely varying friction factors. Some of the $\mu - V$ curves possessed positive slopes, some negative slopes, and some with slopes changing from positive or zero to negative. Since this is practically the only such data in existance it is impossible to justify any general conclusions from the results of these few materials. It is recommended that many more material be so tested so that a general conclusion may be made.

Thesis Supervisor: Ernest Rabinowicz
Title: Assistant Professor of Mechanical Engineering

Massachusetts Institute of Technology
Cambridge 39, Massachusetts
May 23, [illegible]

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In accordance with the regulations of the Faculty, I hereby submit a thesis entitled [illegible] in partial fulfillment of the requirements for the degree of Naval Engineer.

ACKNOWLEDGMENT

The author wishes to express his thanks to the personnel of the Lubrication Laboratory for their help in making possible the obtaining of this information. Mr. Kingsburg and Mr. Purdy were particularly helpful. The author is grateful to Professor E. Rabinowicz for his encouragement and guidance as thesis supervisor.

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INTRODUCTION

Importance of Friction

The very existance of the world is dependent upon a phenomenon we call friction. It is evidenced in widely differing and opposing means. Friction prevents motion, makes motion possible, and it permits us a control over most motion. This applies to practically everything on earth. Friction holds objects in place when we set them, it makes motion possible in all ways from rolling wheels to sliding skis, and it makes starting and stopping motion possible as easily illustrated in accelerating and decelerating a vehicle. It is easy to think of ways which friction is involved importantly in practically all natural and man-made operations.

Friction is often commonly considered undesirable in our machines, etc., where it costs us money in inefficiencies but the truth is that practically none of these machines, etc., would function properly if it were not for the presence of friction. We are actually completely dependent upon friction for our very existance and since it is important we need to understand all we possibly can about it in order to most effectively make use of it where we desire to and to limit or control it elsewhere.

Frictional Phenomenon

Friction is the force exerted on each of two surfaces in contact

by one another in a direction parallel to the plane of contact. Coulomb in 1781 discovered a clear distinction between static and kinetic friction. He observed at that time that kinetic friction was nearly independent of the speed of sliding. He pursued the idea that friction might be due to some molecular adhesion between surfaces inherent in all materials to various degrees. He dropped this idea on the theory that if it were so the friction should be proportional to the area of the sliding surfaces. He finally concluded that friction primarily was the resistances of the asperities of one surface to being lifted and pulled over the tops of the asperities of the other surface.[1] Coulomb was partially right in both of his ideas of mutual adhesion and asperity resistance. He could, however, not rationalize these views during his time.

Today our theory for the cause of friction is that this force between two surfaces in contact consists of two primary parts: 1 - shearing, which is the actual shearing or tearing apart of minute weldments or bonds between the surfaces, and 2 - ploughing, which is the riding over of the asperities of a surface over the asperities of the other surface; this occurs simultaneously to both surfaces to make up the total ploughing. The real area of contact between the two surfaces is between tallest of their asperities which naturally come in contact first.[1] This is similar to pressing the bristles of brushes together. At first only a few of the bristles will touch but as more force is used in pressing them together the longer bristles, first in contact, slip sidewise or bend

by one another in a direction parallel to the plane of contact. Coulomb in 1781 discovered a clear distinction between static and kinetic friction. He concluded at that time that kinetic friction was nearly independent of the speed of sliding. He proposed the idea that friction might be due to some molecular adhesion between surfaces inherent in all materials in various degrees. He dropped this idea on the theory that if it were so the friction would be proportional to the area of the sliding surfaces. He finally concluded that friction primarily was the resistance of the asperities of one surface to being lifted and pulled over the tops of the asperities of the other surface.(1) Coulomb was partially right in both of his ideas of mutual adhesion and asperity resistance. He could, however, not rationalize these views during his time.

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causing more of the shorter bristles to come in contact. In the extreme the two brush handles, holding the bristles, may be pushed almost together if enough force is used. This is quite similar to what happens when any two surfaces are pressed together. The tallest or longest asperities come in contact first and bear the force of pressing over their minute areas of contact. As known from Strength of Materials the material will strain a given amount under a given pressure or force in this case.* This permits some of the shorter asperities to come into contact. This process continues until the force is balanced. This deformation takes place on both surfaces to different degrees depending on material properties and the surface finishes. This process accounts for the difference between "apparent" and "real" areas of contact, where "apparent" is what you would commonly note by eye and "real" is the actual area of contact between the asperities actually in contact.

Shearing is the breaking of weldments between these deformed asperities which are in intimate contact with each other. Sometimes the break occurs right in the "real" surface but generally particles of the two materials are torn away adhering to the other surface. This constitutes wear. The formation of these asperity weldments depends on many factors but for a given pair of surfaces it depends primarily on the force between the two surfaces and the time that a "real" contact is made between two particular points - that is generally the longer time, speaking even so of very short times, the two points

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* In accordance with the general law of Hooke.

have to form a weld the stronger it will be. This may be due to the fact that dealing on the microscopic scale that we are considering a definite time lapse is required by the asperities for bonding. We know that with movement, sliding, heat is dissipated and must be conducted away from the surfaces through the materials concerned. This heat conduction requires time and causes a local softening of the points of surfaces in real contact. This effect can make the weldments form easier and at the same time if the weldments are still soft when sheared the shearing or tearing will be accomplished by less effort. This is one part of the friction force.

The ploughing part is the force required to cause the interlocking asperities to ride up and over or around each other. Under different conditions this may take different means of accomplishment. If the materials are very hard then this term may primarily be the work of causing the asperities to seek new paths during the motion without altering the asperities themselves. This would be a true riding up and over or moving sidewise and around interdicting asperities. However, it seems more logical to assume that this occurs to some extent but that, no doubt, the true behavior is that the movement of the asperities of one surface up and over and around the asperities of the other surface is accompanied by some deformation, both elastic and plastic, of the asperities, usually of both surfaces. This probably is a plastic "mashing" of the asperity peaks and a sidewise slip of the asperities. This is the other part of friction as seen today.

All of these components of friction require a force in order to occur. All of them depend on the force exerted normal to the apparent surfaces holding the materials together and the surface finishes. The weldment formation and strength depends on the chemical ability of the two materials to bond together, the temperature of the "real" surfaces and, possibly aside from its effect on temperature, on time - this is velocity of sliding. No doubt that with some materials there would be definite plastic deformation before shearing the weldments; this depends on the physical properties of the materials concerned. However, that portion where deformation takes place falls into the ploughing part. This whole process of the shearing portion of friction might be likened to an object attached to a table by sticky glue. It is bonded. If left to sit for a longer period it will be a stronger bond. With lots of glues if the temperature is high it will become not so firmly bonded. If you attempt to move the object from the table while the glue is yet sticky part of the glue will break almost immediately and some of it will stretch or deform both elastically and plastically until it reaches some point of stress when it will break loose also. This is a rough parallel but it transmits the basic idea of the shearing portion of the friction force.

The ploughing portion is dependent upon, in addition to normal force and apparent surface finish, the physical properties of the materials, temperature, and the velocity of sliding. This portion can roughly be likened to a boat in the water. A ship actually compresses

the water immediately over which it rides - it increases the pressure in the water as it rides up over some of it - this is what causes pressure actuated mines to function as a ship passes within its lethal range. While some of the water is forced down and under the hull the rest is pushed to either side - the ship or boat hull is making a furrow through the water. All of this requires force to push the boat through the water. In this analogy the ship or boat is the asperities of the harder material. In some cases it is possible that the two materials would randomly change partners in the analogy. In the process of friction this ploughing elastically and plastically deforms the asperities surfaces. This requires force.

This has been an explanation of the microscopic cause of friction. It is with these views in mind that this thesis is done. It is in the light of this approach to the mechanism of friction that the explanation and discussion of the results will be undertaken.

Kinetic and Static Friction

As previously mentioned Coulomb observed that kinetic friction was nearly independent of sliding velocity. This is true generally within the ranges of sliding velocities normally noted. He also noted that there was a definite difference or change in friction between kinetic and static condition, static friction being notably larger than kinetic. Kinetic as used above referes to normally noted sliding velocities. Static as used above is somewhat unknown; truly it refers to no sliding velocity whatsoever. However, is it not possible that this static

friction of Coulomb's may or may not be actually the true static friction. He did not investigate very low sliding velocities - microscopic velocities. This has not become of interest until just recently. It may be possible that Coulomb's static, maximum, friction might occur at different very low sliding velocities lying in the range from zero, true static, up to sliding velocities approaching the normally observable ones.

Not knowing the true behavior of friction at very low sliding velocities it remains that the friction factor, μ - ratio of friction force to normal loading on the surfaces - may follow any one of a number of different paths between zero velocity and the points where friction becomes nearly independent of sliding velocity. Different materials may behave differently in this region. Some may follow one general relationship to sliding velocity and others different relationships within this range. Figure I gives an example of some of the general relationships that may exist in the region from zero up to normal sliding velocities. One must remember we are talking about very low sliding velocities, approaching zero and on the order of 10^{-4} to 10^{-8} centimeters per sec. This is imperceivable to the naked eye.

Stick-Slip

It has been shown that when the sliding friction between dry solid surfaces decreases as the sliding velocity increases, the sliding does not proceed smoothly but in a jerky fashion; we call this stick-slip [2]. The force tending to cause sliding causes the two surfaces to

"break" away from one another and sliding occurs for a short time until the surfaces stick together again. This repeated action is the sort of thing that we call stick-slip. An example, known to all of us, might be the occasional bumpy, jerky path of a piece of chalk over a blackboard. Sometimes this is quite noticeable as the chalk seems to jump rapidly as we write, while at other times the jump or time interval between periods of sticking are much shorter and a nerve grating noise occurs. We have all experienced both of these I am sure. These occurances tell of the type of frictional behavior I am speaking of as stick-slip but they do not justify any great interest in this particular phenomena.

In machinery this same type of behavior may logically exist even though it is not as noticeable to us or possibly immediately recognized as the same general phenomena. The Navy encountered this problem in their great emphasis on noise reduction for naval machinery - primarily submarine machinery. This oscillating motion, set up by stick-slip, excites vibrations in the sliding members and may result in considerable noise being produced. This is heard by us as squeaking of the joints of furniture, auto bodies, etc. As has been stated the Navy encountered this in shaft squeal - propeller shafts turning slowly in stern tubes[(3)] - and no doubt other machinery noises. This stick-slip may well be a problem in delicate control mechanisms where very rapid responses to quite small applied forces or torques is desired. It is felt that this phenomena can best be studied at low sliding velocities. Therefore, in addition to interest in just trying

to understand the basic mechanism of dry friction the behavior of friction at very low sliding velocities is of interest from the stick-slip viewpoint for immediately encountered problems. This warrants some specific investigation and research. This research seems necessarily to take the form of accumulating a large amount of data on the behavior of the friction of many widely differing materials sliding on each other at velocities approaching zero. This will permit the friction factor versus sliding velocity curves to be extended toward zero velocity. After a general accumulation of data of this sort possibly some general conclusions may be drawn relating the low velocity friction behavior to some characteristic or characteristics of the material, hardness, atomic structure, or such. A long time will be required for even an approach to this thorough understanding.

Previous Work Done

The work in this field has been accomplished primarily at MIT during the last five years under an Office of Naval Research contract. The work has been carried out under the Friction and Lubrication Labratory which is under Professor Rightmire, in charge, and Professor Rabinowicz. The first problem was instrumentation capable of measuring frictions at the desired very low velocities. During 1950-1951 Leif Arnesen worked on the project and was unsuccessful in designing the apparatus necessary to adequately carry out the measurements. F. Heyman* took up the work of this project in 1951

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*Now with Westinghouse Electric Corporation

and by 1954, after many difficulties and obstacles encountered, developed the apparatus which now can successfully carry out the necessary measurements. His contribution was great in the development of the apparatus even though he actually did not get any reproducible results from the material testing. This apparatus was used in gathering the very low velocity friction data of this thesis. A very good description of this apparatus is given in a paper published in the Review of Scientific Instruments.(4) Schematic diagrams of the low velocity machine components are shown in Figures VI, VII, and VIII. The descriptive portion of this paper may be found in Appendix A. The apparatus used in obtaining the higher velocity data - velocities above 10^{-3} cms. per sec. - was a standard friction measuring apparatus operated at the extreme low end of its speed range.

The actual test work accomplished since development of the apparatus has been in conjunction with other projects that were in progress so advancement in this field has been slow. However, the gathering of data on this project is a very slow process anyway. The information that has been obtained in this region is presented in Figures II through V.(5) These are contributions from Professor Rightmire, Professor Rabinowicz, Mr. F. Mysliwetz, and Mr. O. Heddon. From these Figures, II through V, it can be seen that different materials have friction factor-sliding velocity curves of varying types. No conclusions can be drawn on so few curves. It will also be quite difficult to distinguish curves of types B from C and D from E unless

FIGURE I
VARIOUS POSSIBLE μ-V CURVES

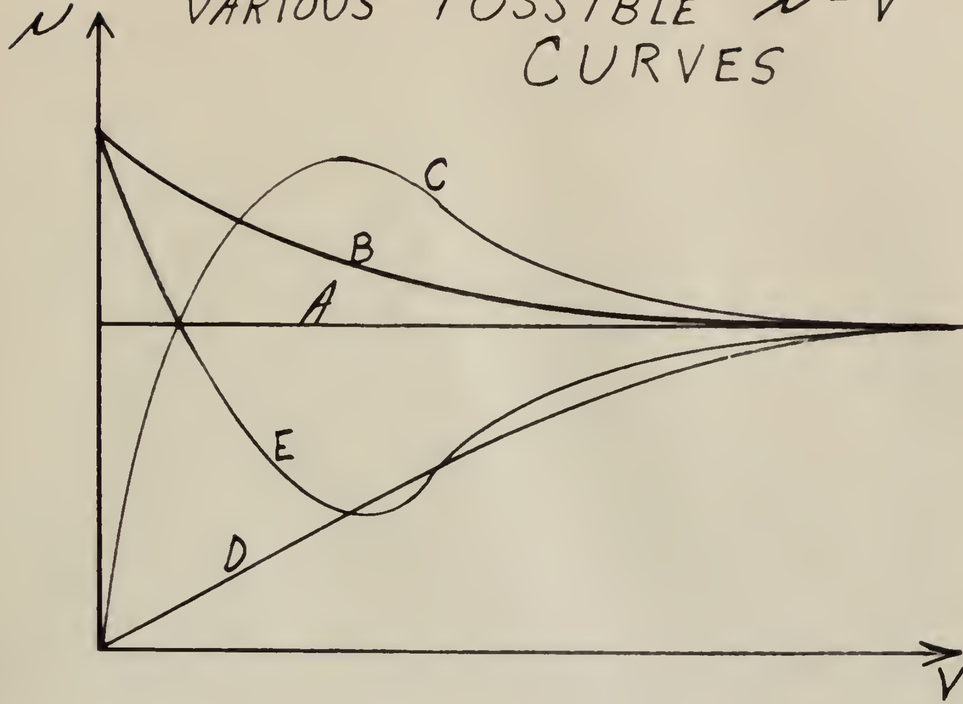
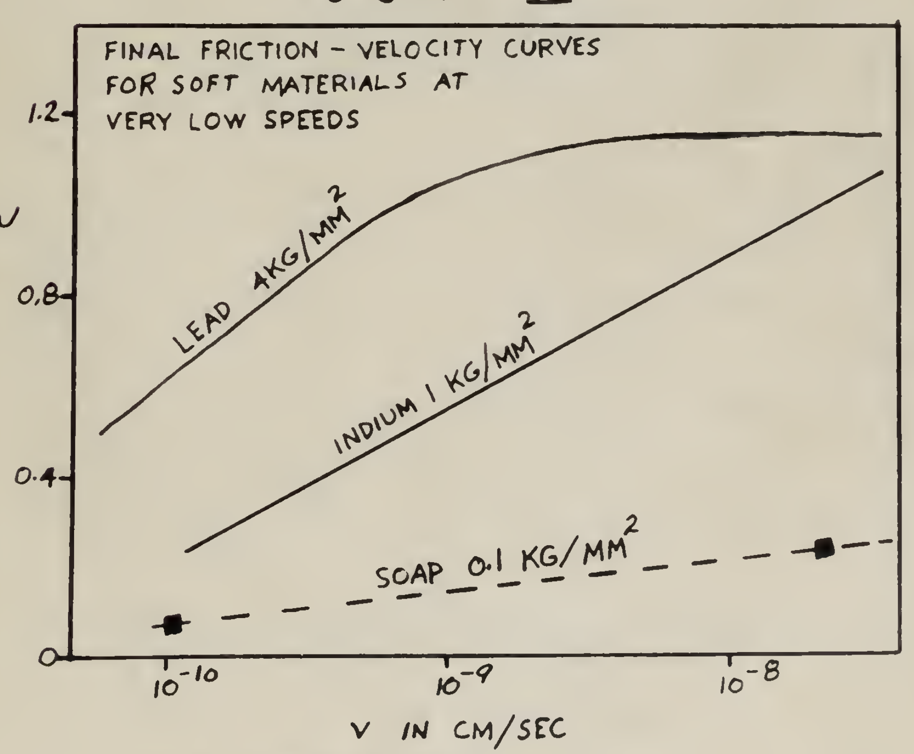


FIGURE II



Extracted from

FIGURE III

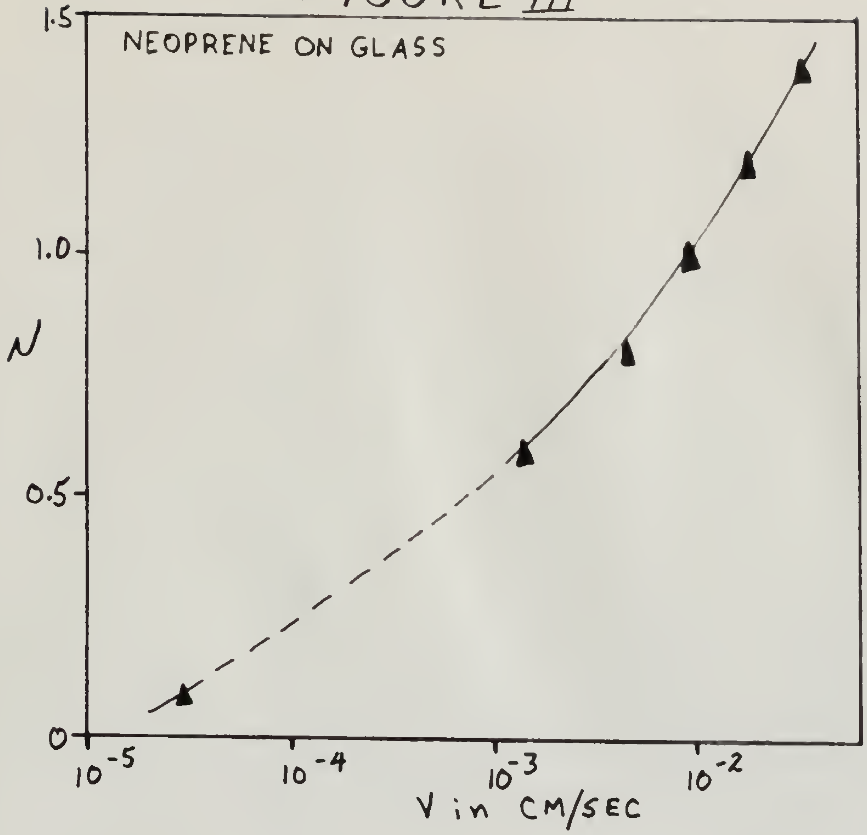
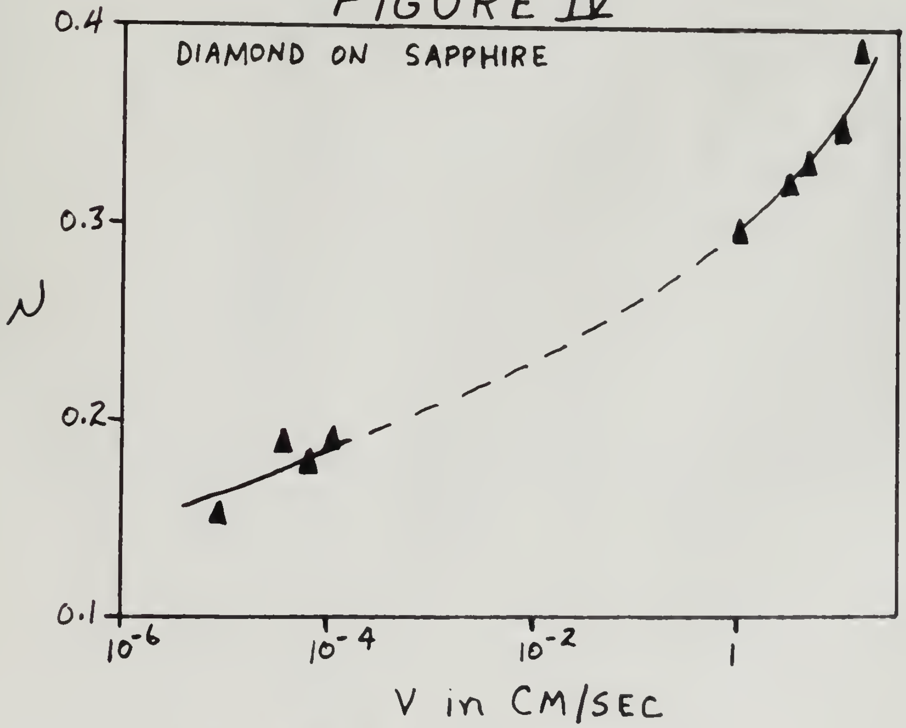
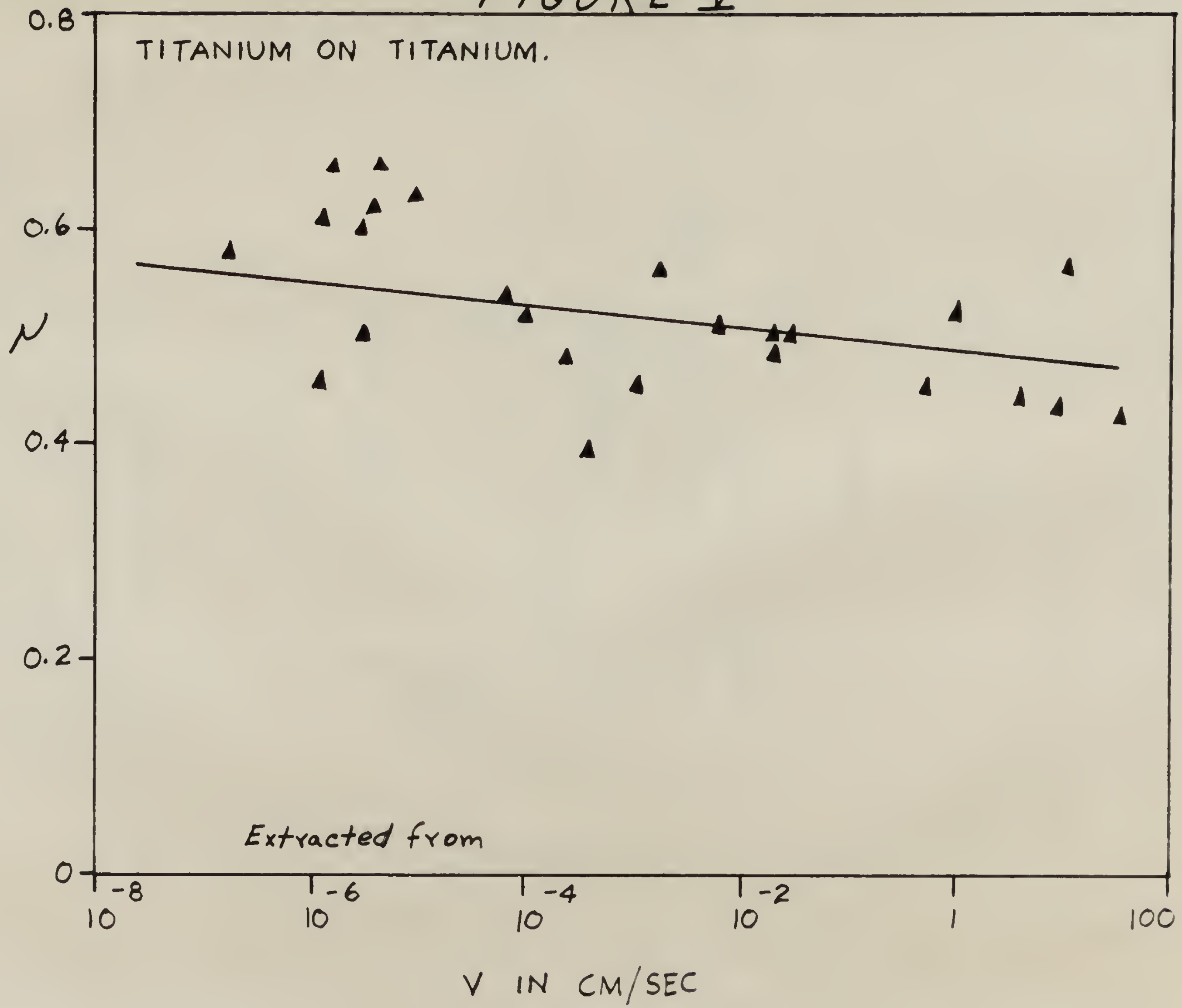


FIGURE IV



Extracted from

FIGURE V



TITANIUM ON TITANIUM.
0.8
0.6
0.4
0.2
0
μ
Extracted from
10^-8
10^-6
10^-4
10^-2
1
100
V IN CM/SEC

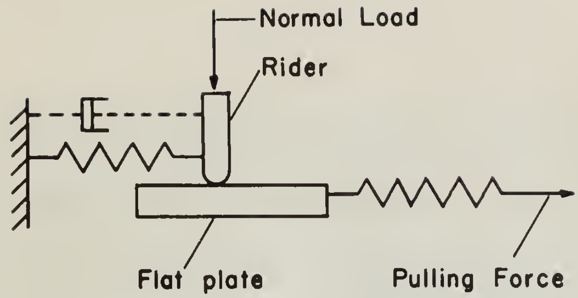


FIGURE VI.

The Driving Mechanism

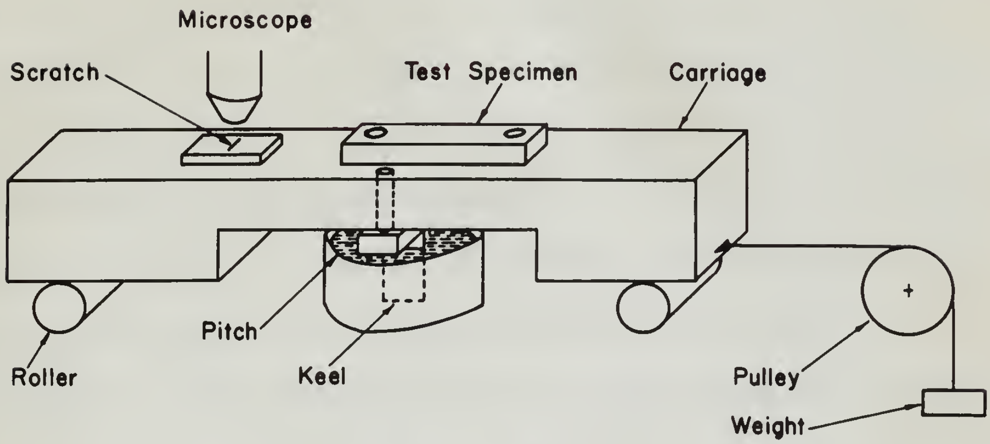


FIGURE VII

The Measuring Device

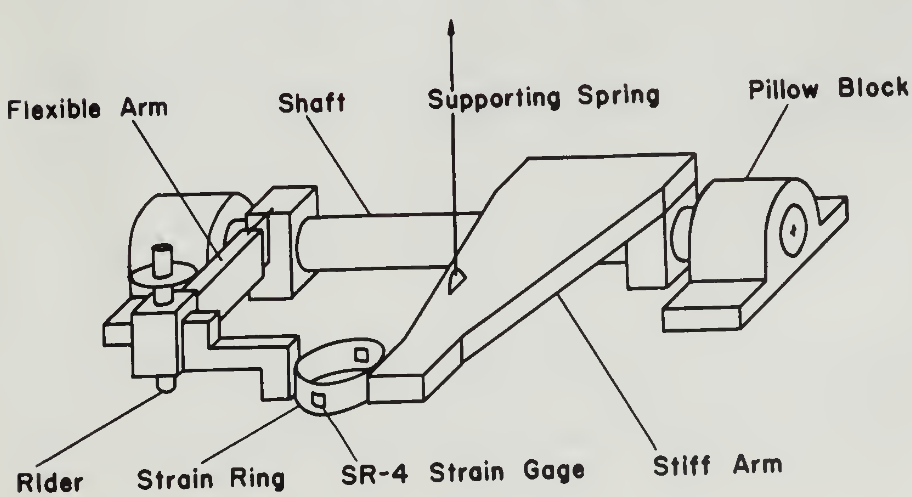


FIGURE VIII.

we are sure we can locate the appropriate humps first. The humps of C and E may be so very close to zero velocity that as far as we are now capable of investigating these curves may appear as B and D respectively. It is also possible to confuse B with A if the slope should be very nearly zero.

One thing that is shown by past work is that at the very low velocities there is a varying relationship between friction and sliding velocity - that friction is no longer nearly independent of sliding velocity, for some materials at least. At this time no general conclusion may be drawn, however. Curves such as Figures II through V must be determined for very many materials before drawing generalities from specific cases. It is the purpose of this thesis to contribute as much as possible to the accumulation of these relationships of friction factors to sliding velocities in the very low velocity range.

PROCEDURE

Calibration

The microscope used for measuring distance traveled by the sample during the time interval of the run was calibrated against an optical calibration grid. This grid was a product of Central Scientific Company. The grid was 2000 lines to the inch. The microscope was first calibrated using the above grid for inches per scope unit. This value was then converted to centimeters per scope unit. The value for my eye on the scope calibrated to be 0.0002441 cms. per scope vernier unit. The Sanborn Recorder used to record the strain gauge readings was calibrated before each series of tests - a series of tests being all recordings on one material and made on one day. This calibration was accomplished by applying known loads to the strain gauge, recording the reading, and then unloading the strain gauge after each loading to obtain a zero point. This procedure was carried out several times using different loads and establishing an average of these readings for both the zero point and the scale of the recorder paper grid. The reference marker, mentioned in the description, was adjusted to a convenient value so that system drift could easily be detected during a run.

Surface Preparation

The surface of the material specimen was prepared by finishing with successively finer grades of emery paper, starting with grade 1/0

emery paper and proceeding through 4/0. The metals, except for aluminum, produced a good, apparently polished surface finish with 4/0 grade paper. Aluminum and the plastics tested seemed to have a smudged dirty surface finish after polishing with 4/0 paper. Each of these was finished with the finest grade of emery paper, courser than 4/0, that produced an apparent polished smooth surface. The finest emery paper used on each respective specimen is noted in the tables I and II of appendix B.

The upper friction surface used was an eighth inch hemispherical plain steel rider in all cases tested. This surface was polished to an apparent smooth finish using 4/0 emery paper on it while it was rotating in a drill chuck.

Test Procedure

The normal load between the rider and specimen surfaces for these tests was standardized at 100 grams for the very slow velocity apparatus and 200 grams for the standard apparatus. After placing the rider arm in place the weight of the arm and associated apparatus was taken up by tension of a spring adjustment. This permitted the rider surface to contact the specimen surface with practically zero normal force between them. Placing 100 grams on the rider arm in its proper position assured knowledge of the normal loading used in order to accurately compute friction factor as the ratio of friction force to normal force. By varying the pulling force on the drive mechanism the velocities were varied. The Sanborn Recorder trace recorded the respective friction

forces as sensed by the strain gauge.

The apparatus when first started was permitted at least two hours to accelerate to a steady state velocity. This was necessary, although possibly excessive, to permit the wave system, etc., in the pitch tank to reach a steady state. The pulling force was varied without any other interruption to the running apparatus. At least thirty minutes were permitted between position readings in order to insure steady state conditions had been reached. At each pulling force, the distance, measured by the microscope, the specimen moves in a period of time was recorded.

Data (See appendix B)

Having notes of the distance moved and the time elapsed the sliding velocity was computed in each instance. Having the recorder tracing of friction force over the interval of time concerned an average friction force was established. Having the average friction force and the normal force an average friction factor was computed for that particular velocity. I wish to emphasize that actually both the average friction factor and the sliding velocity are measured quantities although I might have spoken of them previously as computed. This only referred to a mechanical, mathematical operation on actual measured quantities.

In using the standard friction apparatus the sliding was done in a circular path - the specimen revolving off-center under the rider.

In this case the frictional force was recorded in the same manner as for the slow motion apparatus. The Sanborn Recorder in this case recorded also the rotational speed of the specimen. By knowing, then, the rotational speed and by measuring the diameter of the circular path traveled the sliding velocity was easily obtained. In the same manner as before the friction factor was obtained.

The data as then compiled was plotted for each material tested giving a friction factor versus velocity curve for each.

RESULTS

The materials tested were some plastics and a few metals as follows:

<u>Plastics</u>

1. High Styrene - Figure IX
2. Polyethylene - Figure X
3. Vinyl Chloride - Figure XI
4. Polyester - Figure XII
5. Epoxy - Figure XIII

<u>Metals</u>

6. Zinc - Figure XIV
7. Phosphor Bronze - Figure XV
8. Aluminum - Figure XVI

The results of friction factor versus sliding velocity for these materials are presented in the form of the following curves, figures IX through XVI respectively.

FIGURE IX

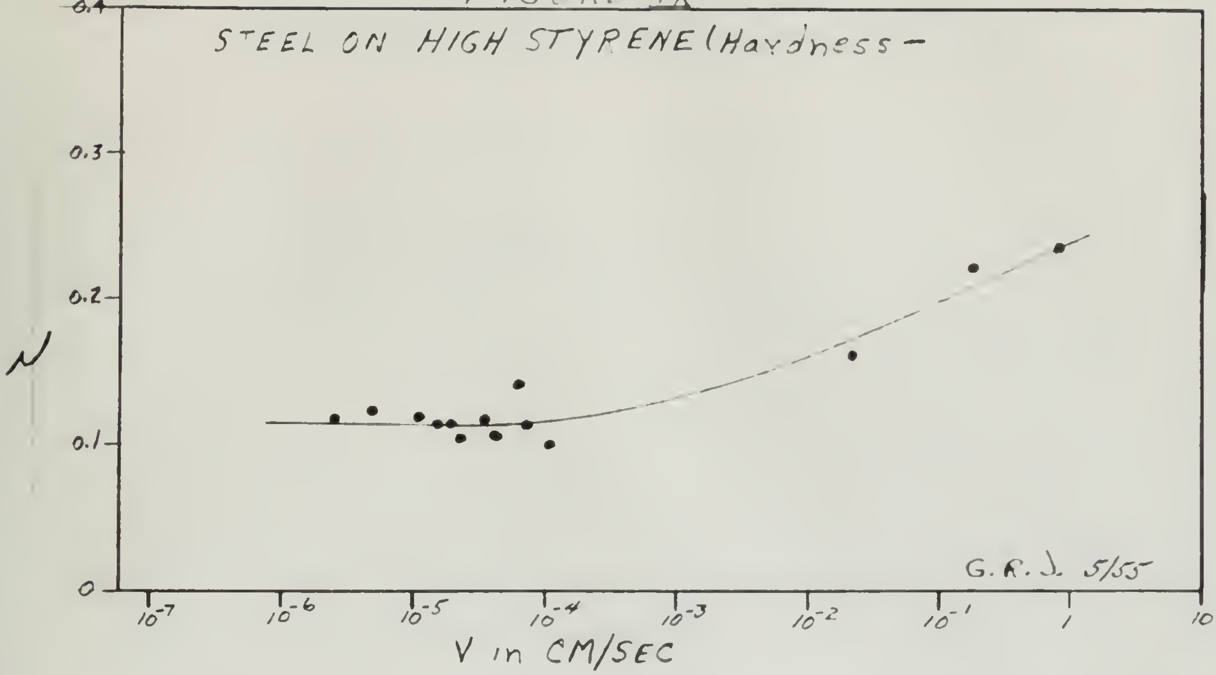


FIGURE X

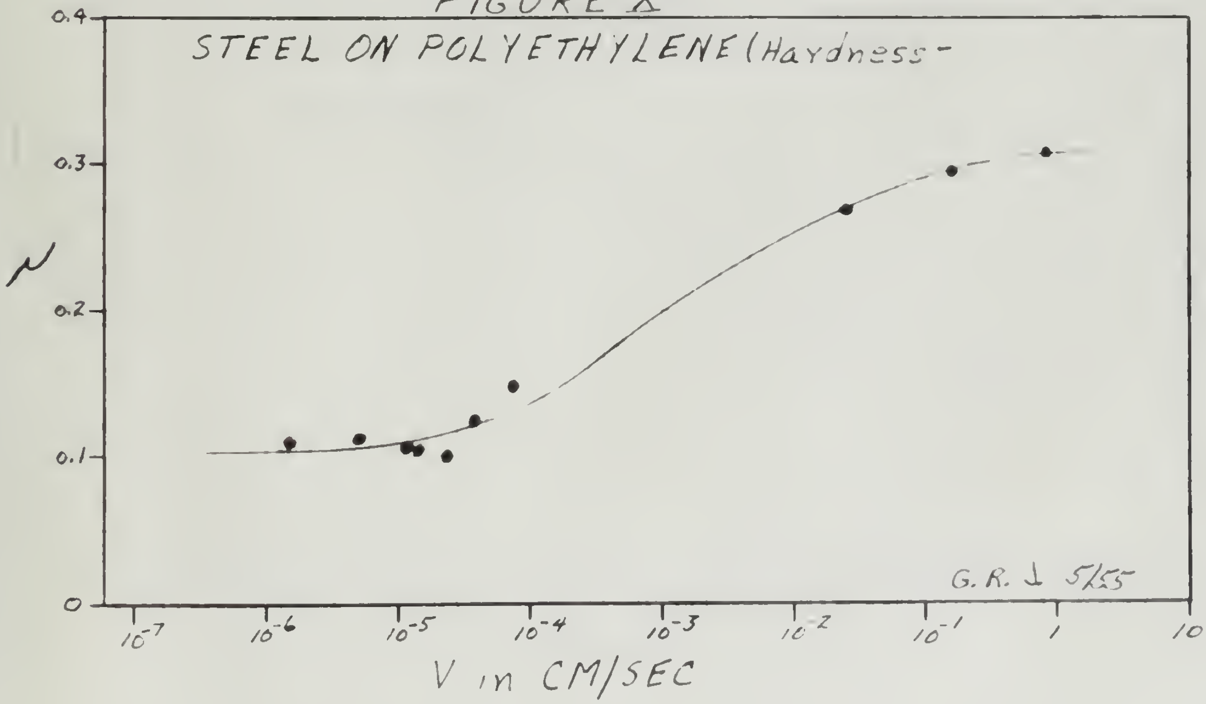


FIGURE XI

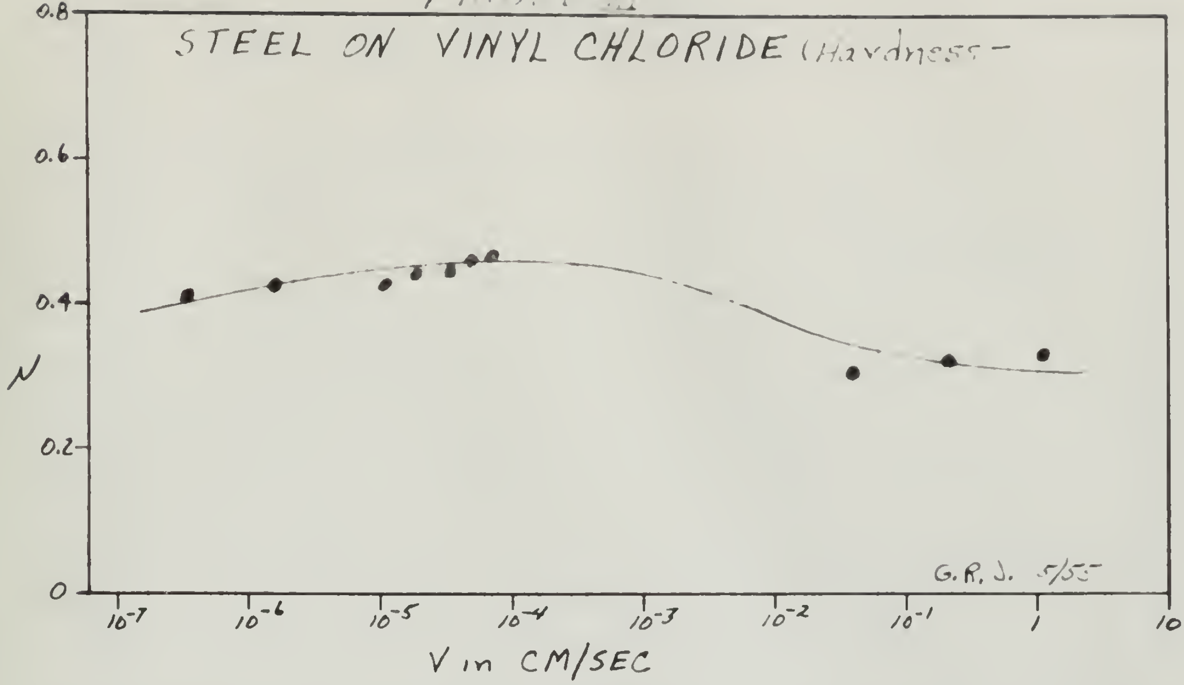


FIGURE XII

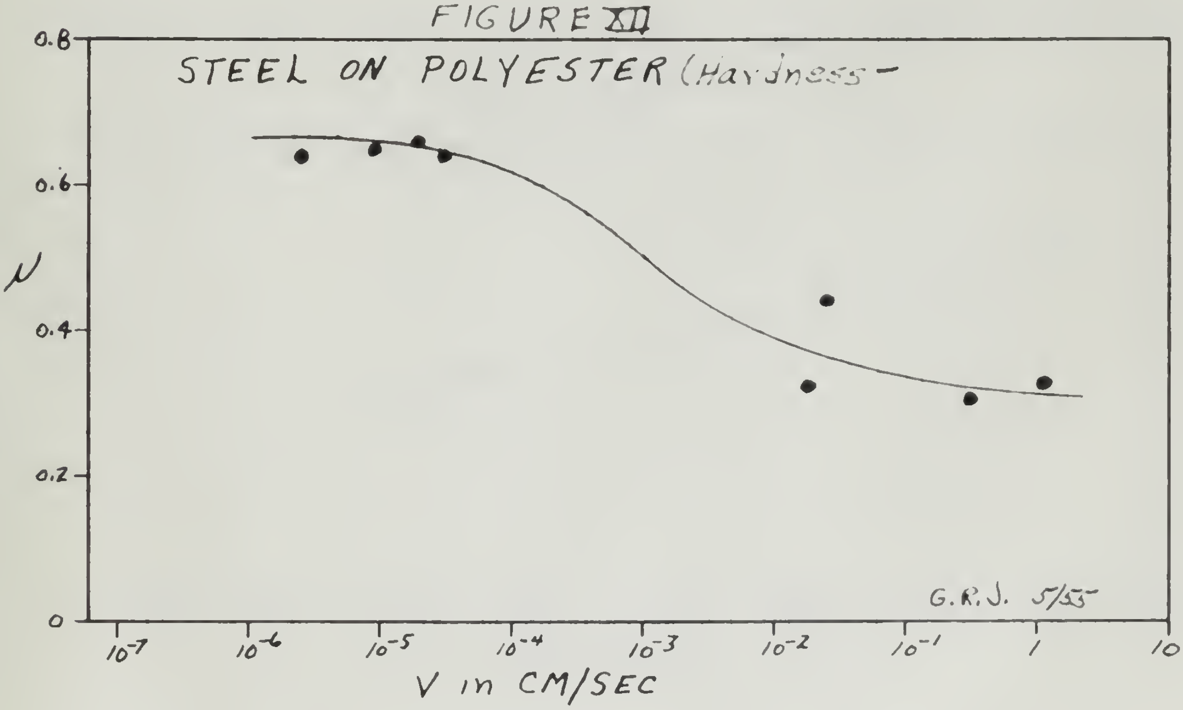


FIGURE XIII

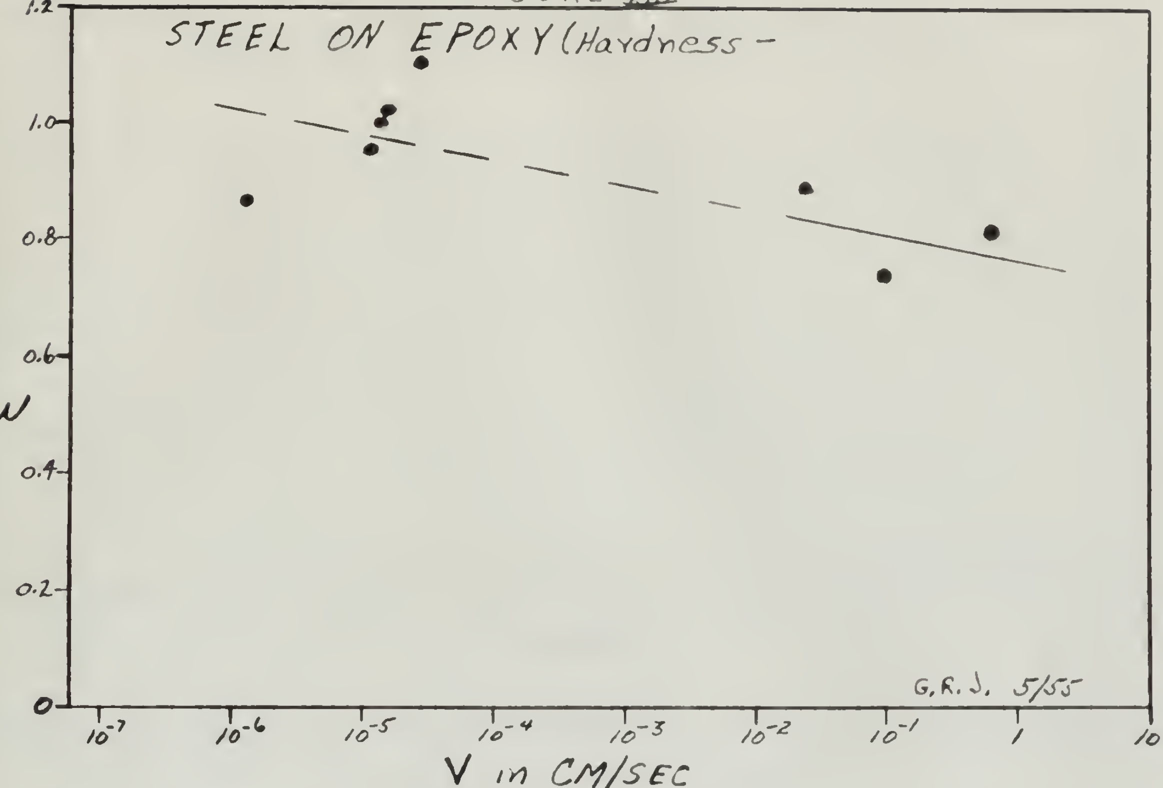


FIGURE XIV

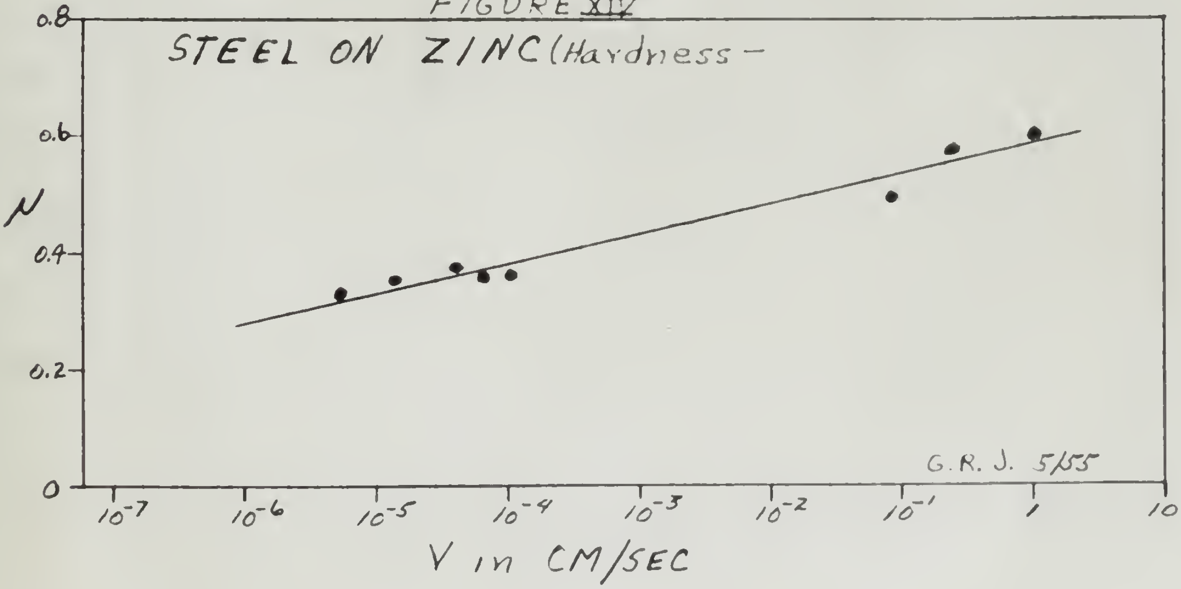


FIGURE XV

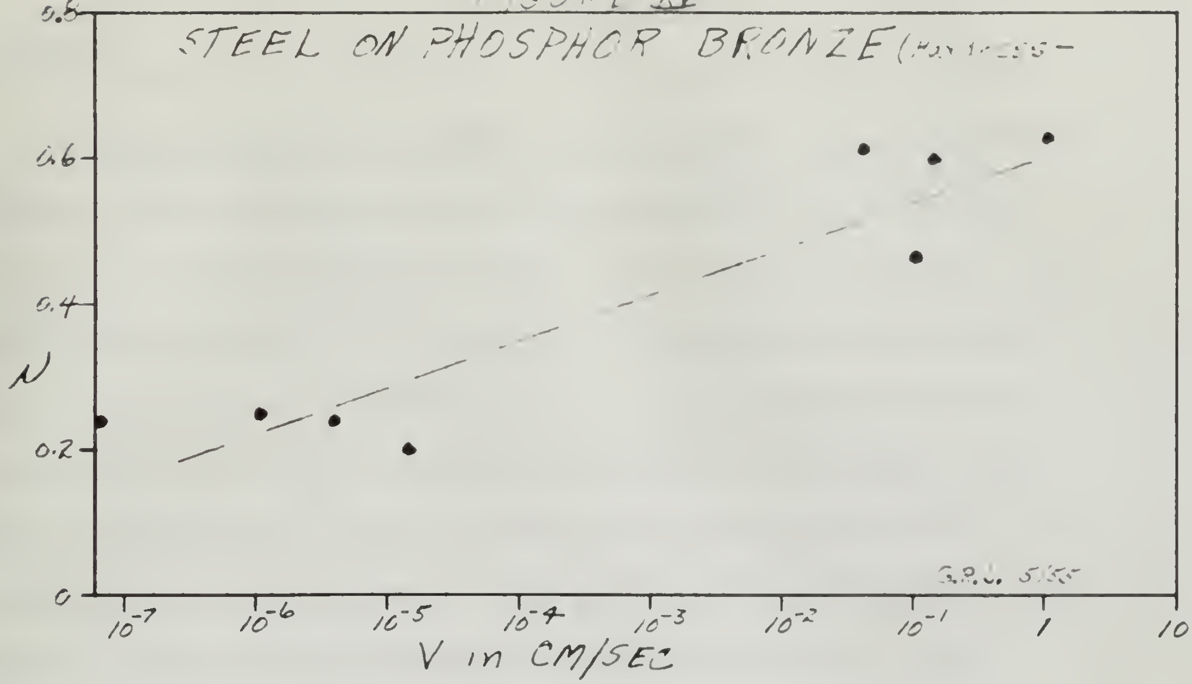
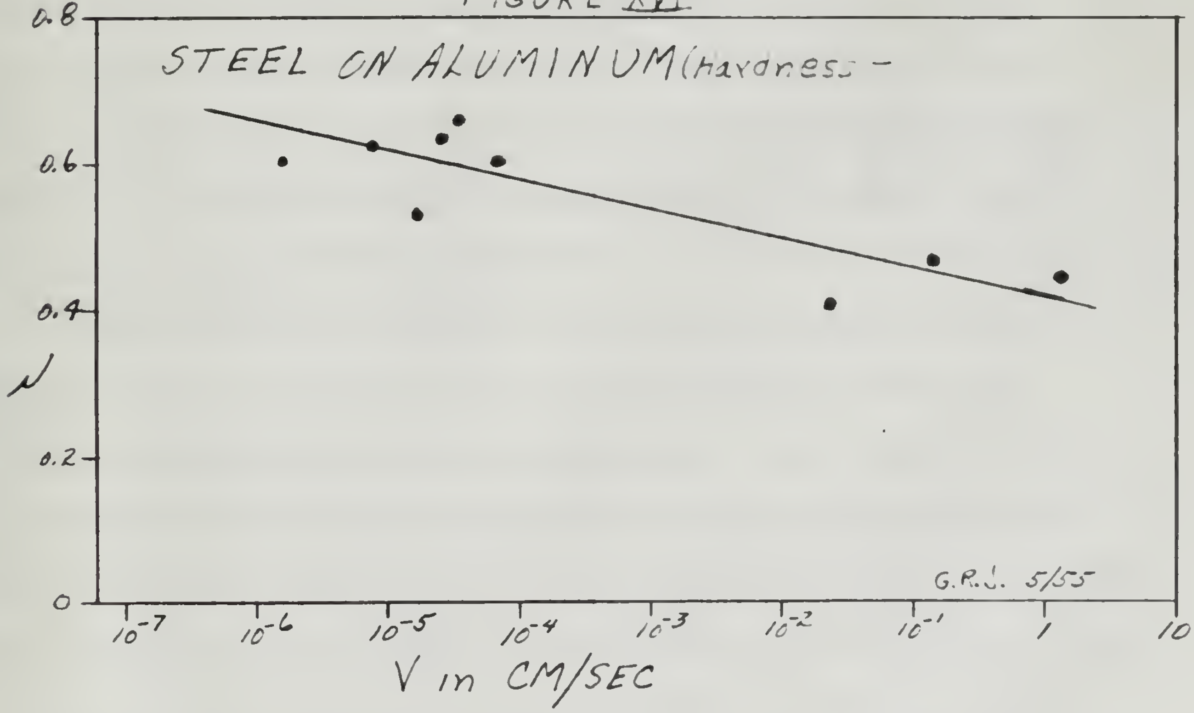


FIGURE XVI



DISCUSSION OF RESULTS

Plastics

Both High Styrene and Polyethylene behaved in very similar manners. Their friction factor, or coefficient of friction, was fairly low at low sliding velocities, on the order of 0.11 at velocities of about 10^{-5} cms. per sec. Information available from higher velocity ranges, 10^{-2} to 1 cm per sec., indicates that the slope of the curve, $\frac{d\mu}{dV}$, increases rapidly up to this point. The slope at the higher velocities appears to again approach zero indicating possibly that this is the peak of the curve. These curves could be similar to either curve C, D, or E of Figure I. These curves would have to be continued further to the right, to higher velocities, in order to determine a C or D type curve and to lower velocities to determine an E type. These materials behave similarly to soap.* The humps or peaks of these curves have not been reached within the range of these experiments.

Vinyl Chloride and Polyester within this same region of examination exhibited humps or peaks or at least indicated that such existed to the left of this experimental range. These curves could be similar to types B or C of Figure I. It seems doubtful that they would be similar to type E which would necessitate a minimum at higher velocities as well as a maximum at lower velocities. Here again, these

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* Discussed with Professor E. Rabinowicz who has done this sortof investigation on soap.

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two materials appeared quite similar to each other in the shape of their curves. Time did not permit measurement of the hardness of these materials as was intended. However, it appeared that Vinyl Chloride and Polyester were harder than High Styrene and Polyethylene. This may be a very important property in determining the sliding velocity at which the friction factor reaches a maximum. This is one of the points that, at present, seems so but warrants more research before a generality may be drawn.

Epoxy, the fifth plastic examined, seemed quite difficult to work with. At first appearance it seemed fairly hard but actually over a period of time a quite small force deformed readily - primarily elastically. The curve developed from data obtained is somewhat in doubt. Due to its odd behavior while working with it, I chose to draw a straight dashed line averaging the points plotted. It is quite possible however from the data plotted that the curve may pass through a rather sharp peak in the vicinity of 10^{-4} to 10^{-3} cms. per sec. If this could be established this would be a good example of the type C curve of Figure I.

Metals

The three metals examined were by no means a complete representative cross section of the available metals. Zinc had a steadily rising curve quite similar to that of High Styrene and Polyethylene. Zinc was the softest metal tested - hardness of 32.[6] Phosphor Bronze - hardness 160 - gave generally the same sort of presentation as zinc. This seems

incongruent with our knowledge and intuition about these metals. Aluminum - hardness 35[6] - showed a gentle, apparently, linearly negative slope. This could correspond to curves of type C or B of Figure I. Aluminum seemed to present the most expected behavior of the metals.

General

In general it appears that softer materials have a U - curve possessing a positive slope in the region investigated and that hard materials generally have a negative slope. This may be explained, at least partially, in light of the discussion in the introduction.

If we set a weight on the surface of quite cold molasses in a container, the weight, if not too large, will appear to rest momentarily right on the surface. It will actually be sinking quite slowly into and through the molasses. If pulled or pushed horizontally while practically resting on the surface the weight will move fairly easily. If the weight is permitted to sink way into the very thick molasses it will require a considerably larger force to cause the same horizontal motion by the molasses with this deeper immersion. This is due to increased frontal area which means that more of the molasses has to be pushed out of the way and/or compressed in order to permit the weight to move horizontally. A ship in water is the same problem. If the ship is unloaded and riding high in the water it takes less power, force, to propel it through the water than if it were at maximum load.

Minimum and maximum load correspond to minimum and maximum drafts - depth to which the ship sinks into the water.

This argument may tend to explain the velocity versus time curve for steel or soap that Professor Rabinowicz produced.(5) His curve shows that velocity decreases with time elapsed.

Assuming a given draft or depth of sinking it requires more and more force to push the weight, spoken of before, or the ship at higher and higher velocities. In ships the power required to propel is nearly a function of the third power of the speed. In view of the findings of Bowden and Tabor about teflon* it seems possible that the softer plastics examined may behave similarly. They, like teflon, have low friction factors. If this is true then this particular category of plastics will not form welds readily and may not adhere readily to its companion surface. This would mean that the shearing portion of the friction force would be quite small if not totally negligible. Presuming this, the softer plastics behave quite as would be expected in this region. Their behavior is similar to the ship in the water analogy. As velocity increases the force must increase. The interlocking asperities of the surfaces must deform to permit passage of the other surface's asperities. Depending on the softnesses and relative normal

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* <u>The Friction and Lubrication of Solids</u>, F.P. Bowden and D. Tabor, pp 167, 168.
"With Teflon it was not possible to form a thermal weld even under the most sever conditions of load and speed....This resistance to seizure and the low coefficient of friction suggest that Teflon may find many important applications as an 'anti-friction' and 'anti-welding' material in bearings and other sliding mechanisms."

load involved this deformation may not be limited to asperities or surfaces alone and then becomes a function of the bulk. Nevertheless, the deformation is all of the same general nature. Sliding velocity determines the rate of this deformation and the rate of deformation determines the forces required to cause it since it is an energy.

In view of all of this it seems that the softer plastics that do not weld to or adhere to their companion surfaces exhibit somewhat of a positive $\mu - V$ curve slope in the region examined.

On the other hand, the harder materials seem, logically, to depend on the shearing portion primarily for their friction. We know that the penetration of the rider, depth to which it sinks, is practically negligible. For the harder materials that weld to or adhere to their companion surfaces the shearing portion of friction seems to be the primary one and ploughing is practically negligible.

Since the more solid the weldments are the larger the required shearing forces it follows that if the sliding velocity causes the character of the weldments to change the shearing force and thus the friction force is going to change similarly. This means that if sliding velocity is increased within this range generally the weldments will not have time to set well. They will be softer due to more heat generated at the surface but less time for it to be conducted away. This will permit the weldments to be sheared easier. This means a negative slope to the $\mu - V$ curve in this region. It is believed that the harder materials exhibit this general behavior generally.

It may well be argued that if the above is correct the $\mu - V$ curve should continue with a negative slope. This is not so. It seems logical to believe that the localized heating due to sliding will also improve the formation of the weldments. At some sliding velocity the two effects will come in balance and the $\mu - V$ slope will not necessarily continue negative.

In the light of this discussion it can be concluded that the friction force is made up of the shearing and the ploughing portions to varying degrees. The shearing portion depends primarily on the mutual ability of the surfaces to weld together at points. The ploughing portion depends primarily on the hardness and the elastic and plastic characteristics of the two materials in contact.

If the materials were quite hard and they are mutually adhesive - tend to form welds - then the ploughing term would be quite small compared to the shearing term. In these cases the surfaces are presumed normally smooth. The ploughing term would consist of just the force deforming the asperities in order to permit sliding - the deformation would not go beyond the actual surface itself in these hard materials. Two surfaces with this type interface, I believe, should exhibit a negative slope for the $\mu - V$ curve in the region concerned.

If the materials were soft and do not have a tendency to weld together the ploughing term would be of prime magnitude as compared to the shearing term. No doubt, some shearing will occur as we can

rarely expect two materials to have no mutual attraction, tendency to form welds. The deformation of these materials would seem to extend certainly beyond the asperities of the surfaces and may be of any extent depending on the materials. The $\mu - V$ curve resulting in the above such case could be expected to have a definitely positive slope in the region concerned. It is possible that at some sliding velocity the heat generated might change the tendency of these materials to form welds and thus alter the slope of the $\mu - V$ curve at other velocities.

It seems that these factors - mutual weldability and resistance to deformation - may vary widely and differently from one pair of surfaces to another possibly. Mutual weldability represents the shearing, and resistance to deformation the ploughing. Having varying combinations of these in different sets of sliding surfaces accounts for curves of drastically different slopes in the region examined. The slope depends on the predominance of one of the terms over the other.

High Styrene and Polyethylene, no doubt, do not weld to steel well at all and therefore the ploughing term is predominant and the slopes in Figures IX and X respectively are definitely positive. Vinyl Chloride and Polyester appear to be harder than the previous two plastics so will have a lesser ploughing tendency. The ploughing term in actual force may be larger due to different material properties but the tendency to permit digging in and gouging by the other surface is less. These two plastics may have a stronger tendency to form bonds

with steel. Overall the two effects together - neither particularly being negligible - produce a gentle change of slope from practically zero to a slight negative one. This change may occur when the sliding velocity is high enough to cause a local softening of the surfaces and thus an increased tendency to form bonds. These curves of changing slope are shown in Figures XI and XII. The curve of Figure XIII is in doubt but may be a sharp curve of the type shown in Figures XI and XII with a very definitely defined peak or it may be one of general negative slope. Zinc, represented in Figure XIV, exhibited the same tendencies as did High Styrene and Polyethylene. The Phosphor Bronze results, Figure XV, were not what was expected. They showed a sharply positive slope when it was intuitively felt that the slope should have been quite small and probably negative. This intuitive expectation of Phosphor Bronze concurs with the general discussion offered here. This difference is, as yet, unexplained. Aluminum presented in Figure XVI a most expected curve that has a small negative slope.

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CONCLUSIONS

Various ideas have been advanced in the discussion but I feel that an insufficient number of materials have been examined in this manner to justify any general overall conclusions. I do conclude, however, that the investigation should be carried on until a vast amount of data has been gathered. At that time I feel that some of the ideas herein discussed may be justified as generalities.

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RECOMMENDATIONS

1. In time a large number of materials, both metals and plastics, should be examined.

2. When additional runs are made some should be made using riders made of a variety of materials.

3. In order to more fully define the curves, different keels should be used in the pitch to permit a greater range of velocities to be obtained using reasonable pulling forces.

4. The automatic velocity recording mechanism Professor Rabinowicz is working on should be perfected and installed. This will greatly facilitate velocity determination.

APPENDIX A

Descriptions of the primary components of the very low speed friction apparatus[4].*

The Driving Mechanism

The driving mechanism diagram is shown in Figure VII.

The moving friction specimen is a block screwed rigidly to a carriage which rests on two cylindrical rollers offering negligible resistance to its travel. Fastened underneath the carriage is a detachable keel immersed in a cup of pitch, which in turn is fastened to the base, the latter being a heavy block carried on antivibration mounts. Attached to the carriage is a flexible wire that passes over a pully and carries a weight pan at its end to provide the pulling force.

The pitch is initially heated and poured into the cup with the keel in place, and when the carriage needs to be removed it is simply detached from the keel by undoing two set screws, the keel remaining undisturbed in the pitch. Using a pitch of softening temperature 180-200° F and a keel with a cross section 1/2 x 3/16 in., we have found it possible to obtain speeds of from 6×10^{-7} to 1.3×10^{-4} cm/sec by varying the depth of immersion of the keel from 1/2 to 1/32 in., and the pulling force from 150 to 1500 g.

To measure the displacement of the moving specimen, a fine scratch on a small glass block cemented to the carriage is observed through

* Quoted from a paper published in the Review of Scientific Instruments, Vol. 26, No. 1, 56-58, January, 1955 - Friction Apparatus for Very Low-Speed Sliding Studies; F. Heymann, F. Rabinowicz, and G.B. Rightmire

APPENDIX I

1. Description of the pulling mechanism of the very low speed friction apparatus[15].*

<u>The Driving Mechanism</u>

The driving mechanism diagram is shown in Figure VII.

The moving friction specimen is a block screwed rigidly to a carriage which rests on two cylindrical rollers offering negligible resistance to its travel. Fastened underneath the carriage is a detachable heel immersed in a cup of pitch, which in turn is fastened to the base, the latter being a heavy block mounted on antivibration mounts. Attached to the carriage is a flexible wire that passes over a pully and carries a weight pan at its end to provide the pulling force.

The pitch is initially heated and poured into the cup with the heel in place, and when the carriage needs to be removed it is simply detached from the heel by undoing two set screws, the heel remaining undisturbed in the pitch. Using a pitch of softening temperature 180–200° F and a heel with a cross section 1/2 x 3/16 in., we have found it possible to obtain speeds of from 4×10^{-7} to 1.3×10^{-4} cm/sec by varying the depth of immersion of the heel from 1/2 to 1/16 in., and the pulling force from 150 to 1500 g.

To measure the displacement of the moving specimen, a fine scratch on a small glass block cemented to the carriage is observed through

* Quoted from a paper published in the Review of Scientific Instruments, Vol. 26, No. 1, 56–59, January, 1955 - Friction Apparatus for Very Low-Speed Sliding Studies; [illegible], and B.G. Rightmire

a microscope equipped with a micrometer eyepiece. The smallest observable displacement is 5×10^{-5} cm. It was found that at the lower speeds it takes some 30 minutes before a uniform speed is obtained and the driving mechanism is therefore set into motion before the experiment begins.

The Measuring Device

Although we have eliminated stick-slip from the driving mechanism, we have not necessarily ensured smooth sliding, because, since a certain amount of elasticity is mandatory if the friction force is to be measured by means of an elastic deflection, stick-slip can originate in the measuring device of such a friction apparatus shown in Figure VI. However, theoretical and experimental studies suggest that through the use of a sufficiently stiff spring this stick-slip can be completely eliminated or, at any rate, greatly reduced.

In our apparatus, the upper or fixed friction specimen is a hemispherically ended rider held firmly in a flexible arm, which is attached by means of an outrigger (to align the forces) to a stiff strain ring (Fig. VIII). The opposite point on the strain ring is fixed to a stiff arm and both the stiff arm and the flexible arm are held on a shaft supported in two ball-bearing pillow - blocks. To balance this assembly and at the same time minimize the normal load on the bearings, the assembly is supported near its center of gravity by a soft spring. The upper anchorage of the spring can be moved up and down in its columns, and also incorporates a fine adjustment so as to

permit the rider carefully to be brought just into contact with the lower friction specimen. The normal load between the specimens is then determined by weights placed on a pan on the flexible arm directly above the rider.

The whole friction force is transmitted by the flexible arm wholly through the strain ring to the stiff arm and is measured by four SR-4 wire-resistance strain gauges cemented to the strain ring and connected to a Sanborn Recorder. The stiffness of the ring is such that a friction force of 50 g - a common value - produces a deflection of 7×10^{-4} cm., and the sensitivity of the friction measuring device is about 1/4 g.

During the long runs that are necessary, a method of checking on the drift of the recorder is desirable, and for this purpose a "dummy transducer" box was constructed. This contains high - precision fixed and adjustable resistors forming a bridge circuit comparable to that of the strain gauges on the ring, and a switch by means of which this circuit can be shunted at any time into the recorder channel in place of the strain gauges. At the beginning of a run, the box can be adjusted to give a reading equal to the no-load reading of the strain ring, and subsequent switching back to the box will disclose any drift in this zero reading.

APPENDIX B

ORIGINAL DATA

Very Low Velocity Friction Machine — Table I — Appendix B

Run	Date	Specimen	Rider	Normal Force	Pulling Force	Scope Units Moved	Cms. Moved	Seconds Elapsed	Velocity (cms/sec)	Friction Coef., fm	Specimen finish
1 (a)	3/23/55	Phosphor Bronze	Steel	100 gr.	750 gr.	42.80	.0105	430	2.44×10^{-5}	0.20	4/0
(b)	"	"	"	"	550 gr.	16.02	.00392	635	6.18×10^{-6}	0.24	
(c)	"	"	"	"	350 gr.	5.49	.00134	1210	1.11×10^{-6}	0.25	
(d)	"	"	"	"	150 gr.	0.67	.000164	1985	8.27×10^{-8}	0.24	
2 (a)	3/29/55	Polyester	Steel	100 gr.	750 gr.	88.11	.0215	420	5.11×10^{-5}	0.64	3/0
(b)	"	"	"	"	550 gr.	63.18	.0154	435	3.54×10^{-5}	0.66	
(c)	"	"	"	"	250 gr.	27.63	.00677	710	9.51×10^{-6}	0.65	
(d)	"	"	"	"	200 gr.	17.85	.00436	980	4.45×10^{-6}	0.64	
(e)	"	"	"	"	50 gr. 100 150	None		900-1200			
3 (a)	3/31/55	High Styrene	Steel	100 gr.	750 gr.	75.10	.0184	225	8.19×10^{-5}	.142	3/0
(b)	"	"	"	"	550 gr.	92.02	.0225	380	5.91×10^{-5}	.118	

TABLE I
(continued)

Run	Date	Specimen	Rider	Normal Force	Pulling Force	Scope Units Moved	Cms. Moved	Seconds Elapsed	Velocity (cms/sec)	Friction Coef., fm	Specimen Finish
(c)	3/31/55	High Styrene	Steel	100 gr.	350 gr.	45.19	.0110	310	$3.55x10^{-5}$	.116	
(d)	"	"	"	"	250 gr.	32.23	.00788	300	$2.62x10^{-5}$	.115	
(e)	"	"	"	"	150 gr.	24.15	.00590	442	$1.34x10^{-5}$	.12	
(f)	"	"	"	"	100 gr.	20.57	.00502	710	$7.08x10^{-6}$	.124	
(g)	"	"	"	"	70 gr.	11.61	.00284	615	$4.61x10^{-6}$	.119	
(h)	"	"	"	"	1050 gr.	113.37	.0276	240	$1.15x10^{-4}$	.102	
(i)	"	"	"	"	900 gr.	74.44	.0184	210	$8.78x10^{-5}$	.115	
(j)	"	"	"	"	750 gr.	45.72	.0112	170	$6.59x10^{-5}$	.108	
(k)	"	"	"	"	550 gr.	62.34	.0152	360	$4.22x10^{-5}$	.105	
4 (a)	4/1/55	Vinyl Chloride	Steel	100 gr.	950 gr.	166.57	.0406	430	$9.46x10^{-5}$	.469	3/0
(b)	"	"	"	"	750 gr.	141.99	.0346	420	$8.25x10^{-5}$	.461	
(c)	"	"	"	"	500 gr.	59.58	.0145	250	$5.80x10^{-5}$	.448	
(d)	"	"	"	"	350 gr.	39.07	.00952	280	$3.40x10^{-5}$	.442	

TABLE I
(Continued)

Very Low Velocity Friction Machine Table I Appendix B

Run	Date	Specimen	Slider	Normal Force	Pulling Force	Sound Units Level	Osc. Ampl.	Magnitude	Velocity (cm/sec)	Friction Coeff., μ	Specimen Finish
(a)	3/31/55	Oak [illegible]	Steel	100 gr.	250 gr.	65.10	.0110	310	2.15x10^-5	.114	
(d)	"	"	"	"	250 gr.	52.25	.00799	300	2.4x10^-5	.119	
(e)	"	"	"	"	180 gr.	54.15	.00590	442	2.31x10^-5	.12	
(f)	"	"	"	"	100 gr.	29.37	.00002	722	2.08x10^-6	.124	
(g)	"	"	"	"	70 gr.	11.61	.00088	619	1.61x10^-6	.119	
(h)	"	"	"	"	1050 gr.	113.57	.0275	260	1.13x10^-4	.104	
(i)	"	"	"	"	900 gr.	74.44	.0106	210	3.76x10^-5	.125	
(j)	"	"	"	"	750 gr.	45.72	.0112	170	3.59x10^-5	.108	
(k)	"	"	"	"	550 gr.	42.34	.0152	360	4.22x10^-5	.105	
4 (a)	4/1/55	Vinyl Chloride	Steel	100 gr.	950 gr.	165.57	.0406	430	9.46x10^-5	.469	3/0
(b)	"	"	"	"	730 gr.	142.95	.0346	420	8.23x10^-5	.481	
(c)	"	"	"	"	500 gr.	59.58	.0245	250	9.80x10^-5	.444	
(d)	"	"	"	"	350 gr.	59.07	.00952	290	3.40x10^-5	.427	

TABLE I
(Continued)

Run	Date	Specimen	Rider	Normal Force	Pulling Force	Scope Units Moved	Cms Moved	Seconds Elapsed	Velocity (cms/sec)	Friction Coef., fm	Specimen finish
(e)	4/1/55	Vinyl Chloride	Steel	100 gr.	150 gr.	22.61	.00552	485	1.14×10^{-5}	.430	
(f)	"	"	"	"	75 gr.	9.46	.00231	775	2.98×10^{-6}	.427	
(g)	"	"	"	"	50 gr.	2.53	.000619	1075	5.73×10^{-7}	.415	
5 (a)	4/13/55	Polyethylene	Steel	100 gr.	950 gr.	111.07	.0271	304	8.91×10^{-5}	.148	3/0
(b)	"	"	"	"	750 gr.	208.06	.051	840	6.08×10^{-5}	.124	
(c)	"	"	"	"	550 gr.	76.21	.0186	430	4.33×10^{-5}	.100	
(d)	"	"	"	"	350 gr.	64.96	.0158	640	2.47×10^{-5}	.104	
(e)	"	"	"	"	250 gr.	21.49	.00525	325	1.61×10^{-5}	.107	
(f)	"	"	"	"	150 gr.	18.51	.00452	530	7.12×10^{-6}	.111	
(g)	"	"	"	"	75 gr.	7.47	.00182	685	7.65×10^{-6}	.11	
6 (a)	4/15/55	Epoxy	Steel	100 gr.	950 gr.	28.80	.00704	260	2.7×10^{-5}	1.025	3/0
(b)	"	"	"	"	750 gr.	21.25	.0052	255	2.03×10^{-5}	1.001	
(c)	"	"	"	"	550	16.32	.00398	280	1.42×10^{-5}	.953	

TABLE I
(Continued)

Very Low Velocity Friction Machine Table I Appendix B

Run	Date	Specimen	Rider	Normal Force	Pulling Force	Scope Units Moved	Cms. Moved	Seconds Elapsed	Velocity (cms/sec)	Friction Coef., fm	Specimen finish
(d)	4/15/55	Epoxy	Steel	100 gr.	300 gr.	4.29	.00105	525	1.99×10^{-6}	.870	
(e)	"	"	"	"	100 gr.	No motion	——	——	——	——	
(f)	"	"	"	"	1300 gr.	24.99	.0061	122	4.98×10^{-5}	1.109	
7 (a)	4/19/55	Zinc	Steel	100 gr.	950 gr.	200.32	.0496	480	1.02×10^{-4}	.365	3/0
(b)	"	"	"	"	750 gr.	194.50	.0475	563	8.41×10^{-5}	.364	
(c)	"	"	"	"	550 gr.	86.28	.0209	335	6.3×10^{-5}	.376	
(d)	"	"	"	"	250 gr.	47.29	.0115	545	2.12×10^{-5}	.353	
(e)	"	"	"	"	150 gr.	14.94	.0037	480	7.6×10^{-6}	.335	
8 (a)	4/20/55	Aluminum	Steel	100 gr.	950 gr.	69.16	.0169	290	5.82×10^{-5}	.660	3/0
(b)	"	"	"	"	750 gr.	60.71	.0147	317	4.65×10^{-5}	.636	
(c)	"	"	"	"	1250 gr.	114.09	.0280	330	8.42×10^{-5}	.602	
(d)	"	"	"	"	550 gr.	31.21	.0076	260	2.92×10^{-5}	.565	
(e)	"	"	"	"	250 gr.	13.79	.0034	380	8.85×10^{-6}	.627	
(f)	"	"	"	"	150 gr.	6.68	.0016	595	2.73×10^{-6}	.602	

Very Low Velocity Friction Machine Table I Appendix II

Run	Date	Specimen	Slider	Normal Force	Falling Force	Scope Deflection	Sec. Moved	Divisions Elapsed	Velocity (cm/sec)	Friction Coef., To	Specimen Finish
(f)	4/15/55	Quarry	Steel	2100 gr.	300 gr.	4.39	.00502	528	$1.79x10^{-6}$	.870	
(g)	"	"	"	"	100 gr.	No motion	—	—	—	—	
(h)	"	"	"	"	2300 gr.	24.95	.0061	138	$4.98x10^{-5}$	1.109	
7 (a)	4/19/55	Zinc	Steel	2000 gr.	750 gr.	204.72	.0496	480	$1.12x10^{-4}$	.495	3/0
(b)	"	"	"	"	750 gr.	194.50	.0475	562	$8.41x10^{-5}$	.364	
(c)	"	"	"	"	590 gr.	26.38	.0229	335	$6.3x10^{-5}$	.376	
(d)	"	"	"	"	590 gr.	47.24	.0115	545	$2.32x10^{-5}$	.353	
(e)	"	"	"	"	150 gr.	14.94	.0037	480	$7.6x10^{-6}$	.335	
8 (a)	4/20/55	Limestone	Steel	2100 gr.	990 gr.	64.15	.0159	250	$5.28x10^{-5}$	.380	3/0
(b)	"	"	"	"	750 gr.	60.71	.0149	317	$4.69x10^{-5}$	.408	
(c)	"	"	"	"	1090 gr.	114.09	.0280	330	$8.48x10^{-5}$	.502	
(d)	"	"	"	"	500 gr.	31.31	.0076	250	$2.96x10^{-5}$	.565	
(e)	"	"	"	"	250 gr.	13.79	.0034	380	$8.95x10^{-6}$	.627	
(f)	"	"	"	"	130 gr.	6.64	.0016	595	$2.73x10^{-6}$	.402	

Standard Friction Machine Table 2

Run	Date	Specimen	Rider	Normal Force	Dia. of Circle(Cms.)	Secs/rev.	Velocity	Friction Coef., fm	Specimen finish
1 (a)	5/10/55	Phosphor Bronze	Steel	200 gr.	2.20	58.2	$1.18x10^{-1}$	.464	4/0
(b)	"	"	"	"	2.21	6.4	1.08	.63	
(c)	"	"	"	"	2.19	104.0	$6.64x10^{-2}$	.615	
(d)	"	"	"	"	2.19	29.7	$2.32x10^{-1}$	.600	
2 (a)	5/10/55	Aluminum	Steel	200 gr.	1.95	26.0	$2.35x10^{-1}$	.470	3/0
(b)	"	"	"	"	1.95	145.0	$4.21x10^{-2}$	.410	
(c)	"	"	"	"	1.96	3.0	2.04	.443	
3 (a)	5/10/55	Polyester	Steel	200 gr.	1.72	175.0	$3.09x10^{-2}$	.322	3/0
(b)	"	"	"	"	1.71	120.3	$4.5x10^{-2}$	.440	
(c)	"	"	"	"	1.70	10.0	$5.41x10^{-1}$	.315	
(d)	"	"	"	"	1.71	3.9	1.38	.327	
4 (a)	5/11/55	Vinyl Chloride	Steel	200 gr.	2.00	102.0	$6.13x10^{-2}$	.305	3/0
(b)	"	"	"	"	2.05	16.3	$3.95x10^{-1}$	.325	
(c)	"	"	"	"	2.05	5.0	1.28	.331	

TABLE 2
(Continued)

Standard Friction Machine Table 2

Run	Date	Specimen	Rider	Normal Force	Dia. of Circle(Cms.)	Secs/rev.	Velocity	Friction Coef., fm	Specimen finish
5 (a)	5/11/55	High Styrene	Steel	200 gr.	2.01	158.0	$4.00x10^{-2}$	.162	3/0
(b)	"	"	"	"	2.01	20.0	$3.15x10^{-1}$	.223	
(c)	"	"	"	"	2.02	7.0	$9.09x10^{-1}$	.237	
6 (a)	5/11/55	Polyethy-lene	Steel	200 gr.	1.90	129.0	$4.63x10^{-2}$	.269	3/0
(b)	"	"	"	"	1.90	21.0	$2.34x10^{-1}$	.294	
(c)	"	"	"	"	1.91	5.4	1.11	.309	
7 (a)	5/11/55	Zinc	Steel	200 gr.	1.90	64.1	$9.3x10^{-2}$	.494	3/0
(b)	"	"	"	"	1.83	13.0	$4.4x10^{-1}$	.576	
(c)	"	"	"	"	1.81	5.5	1.04	.602	
8 (a)	5/11/55	Epoxy	Steel	200 gr.	1.85	136.0	$4.27x10^{-2}$	.890	3/0
(b)	"	"	"	"	1.85	59.4	$9.78x10^{-2}$	.740	
(c)	"	"	"	"	1.87	7.2	$8.18x10^{-1}$	.821	

APPENDIX C

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